LASER BEAM WELDING OF COMMERCIALLY PURE TITANIUM SHEETS

A thesis submittedin partial fulfilment of the requirements for thedegree of

MASTER TECHNOLOGY
IN
METALLURGICAL & MATERIALS ENGINEERING

Submitted by

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DEPARTMENT OF METALLURGICAL & MATERIALS ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY
ROURKELA

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CERTIFICATE

This is to certify that the thesis entitled, “Laser beam welding of commercially pure titanium sheets” submitted by BibhuduttaBishoyi (212MM1414) in partial fulfilment of the requirements for the award of Master of Technology in Metallurgical & Materials Engineering at the National Institute of Technology, Rourkela is a bonafide research work carried out by him under my supervision.

To the best of my knowledge, the matter embodied in the thesis is based on candidate’s own work, has not been submitted to any other university/ institute for the award of any degree.

Date: Supervisor

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ABSTRACT

In the present work, effect of process parameter such as laser power, welding speed, size of beam diameter on the microstructure and mechanical properties on laser beam welding of annealed commercially pure titanium(cp-ti) grade-2 is investigated. Titanium is preferred due to its wide applications in the field of automobile, marine, aerospace, power plant, structural etc. for its light weight, high specific strength, high corrosion resistance, having good mechanical properties at elevated temperature compared to other structural materials like aluminium, steel etc. Laser welding has more advantages over other normal fusion welding due to its low heat input, high cooling rate and high power density. This high power density and high cooling rate of laser welding provides deeper and narrower weld bead results high welding efficiency, smaller heat affected zone, acceptable weld bead profile, less distortion, less residual stress and retain mechanical properties.

Cp-titanium plates of 1 mm thickness were obtained from the commercial market.The laser welding of cp-ti sheet was carried out by using a continuous wave (CW) CO_2 laser at different operating conditions such as laser power at 2kW & 2.5kW, welding speed from 4m/min to 8m/min and laser intensity distribution by Gaussian Mode (0.18mm beam diameter at focus) and Donut Mode (0.36mm beam diameter at focus). Microstructure of weld size and fusion zone were examined by using optical microscope at different magnifications. Weld size was decreased with increasing welding speed and increased with increasing laser power and spot diameter. The initial microstructure of base metal showed equiaxed grains of 'α' and with increasing welding speed and laser power the grain size was increased. At low welding speed, elongated grains were observed in the weld interface. It also showed a sharp interface at large beam diameter (Donut mode). Measurement of micro-hardness was taken across the welding by using micro-hardness testing machine. The Vickers hardness increases from base material to centre of weld region. Tensile testing of the weld was carried out in a universal testing machine and it is observed that tensile strength of weld at different process parameters is approximately equal to the tensile strength of base metal. Comparative studies of process parameters on the laser welding of cp-ti were investigated.

Keywords: Laser welding, CP titanium, Laser process parameter, Gaussian mode, Donut mode,

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Chapter 1

INTRODUCTION

1. INTRODUCTION

1.1 Research background:

Titanium and its corresponding alloys are one of the most widely used groups of metals in structural and industrial applications [1, 2]. Compared to other structural metals and alloys, titanium and its alloys have excellent mechanical properties like high specific strength, fracture toughness, good corrosion & erosion resistance, high stiffness and ability to resist at elevated temperature [3]. These properties make titanium useful for important applications such as medical instruments, human body implant, aerospace, automobile, chemical, petroleum, nuclear and power generation industries [4-7]. Normal fusion welding techniques are the extensively used welding methods for titanium sheet [8]. Large heat input is the main drawback of normal fusion welding. Which decreases its mechanical property during application as it induces large heat affected zone, greater distortion, residual stress, broader weld seam and higher risk of contamination [9]. For better mechanical property; a narrower heat affected zone, less distortion and narrower seam weld is required [10-12]. Laser beam welding (LBW) is widely used in these days to minimize the drawbacks of normal fusion welding processes [13, 14].The welding speed is higher [5]. The weld pool of LBW is much smaller than arc welding due to the small focusing diameter. LBW has high aspect ratio and high welding efficiency [15].

LBW was initially applied for thermoplastics in the 1970s then in later period it was used for various materials such as metal, nylon and polyester [16]. The beam of LBW provides high power density, which facilitates for narrow, deep welding and high welding rates. LBW is a non-contact joining process. Metal pieces of similar and dissimilar types, sheet, film, moulded thermoplastics and nylon, polyester etc are welded through the use of a laser [17]. LBW can join metals with or without the use of filler wire. The resistance to corrosion and properties of the material are conserved as the micro-structural changes restricted by the LBW [18]. Similarly gas shielding is necessary to preserve the mechanical properties by preventing embitterment on weld and improve the coupling between laser beam and highly reactive material like titanium during LBW [19-22]. The LBW joints for titanium alloys have better combination of strength and ductility compared to other normal joining process. LBW of titanium alloys have the highest aspect ratio. Various parameters such as power density, welding speed, beam diameter, pulse width, pulse repetition rate, pulse energy, cover gas flow rate, defocusing distance, beam angle etc. decide the quality of laser welding [23, 24]. Various reports are available on such parameters on the effect of quality of laser welding in case of different materials.

In the present work, an extensive study on effect of process parameters on LBW of commercially pure titanium (cp-ti) sheets is investigated. The important process parameters such as laser power output, welding speed and beam focus diameter (Gaussian Mode and Donut Mode) are considered for the present study. The micro-structural study is investigated by optical microscope and quality of laser welding is estimated through DP test, EPMA, micro-hardness testing and tensile testing.

1.2 Objectives

- LBW of cp-ti sheets at different process parameter – laser power at 2 & 2.5kW, welding speed from 4-8 m/min and beam focus at 0.18 & 0.36 mm.
- Suitable combination of different process parameters to examine their effect on LBW of cp-ti sheets.
- Investigation of micro-structural and mechanical properties of laser welded cp-ti samples

Chapter 2

LITERATURE REVIEW

2. LITERATURE REVIEW

2.1. A brief Overview of Commercially Pure Titanium:

Titanium element is represented by Ti and having atomic number 22. Its density is 4.506g/cm^3 with melting point 1668^{o}C. It has low coefficient of thermal expansion with most useful properties such as high corrosion resistance and high specific strength. Commercial titanium (99.3% pure) has tensile strength of about 430MPa, equal to that of low carbon steel alloys but 46% lighter [3]. However, Ti is 62% heavier, but twice stronger than Al [3]. Titanium is a very high reactive metal. It reacts with oxygen at 1100 °C in air, and at 600 °C in pure oxygen forming TiO_2 [25]. However, the oxide layer prevents the surface from more oxidation. At 550 °C, it also combines with chlorine [26], halogens and hydrogen [27]. Titanium reacts with Nitrogen at 800 °C to form TiN which causes embrittlement and loses ductility [28]. Hence, vacuum or inert atmosphere is suitable for processing of titanium.

Cp-ti experiences an allotropic phase transformation at 880 °C, where alpha (α) phase HCP crystal structure changes to beta (β) phase BCC crystal structure [29, 30]. The temperature of phase transformation depends upon interstitial elements. Elements like C, O and N are strong α stabilizer and increasing the phase transformation temperature. While the β stabilizing elements, are lowering the temperature [31]. The transformation of the BCC β to the HCP α is carried out by a nucleation or martenstic transformation and microstructure depends on composition, cooling rate, cold working and annealing process applied. However, the formation of the grain with different sizes and shapes depends upon the cooling rate. When the cp-ti is annealed in the beta region at 1000^{o}C and then cooled to room temperature by water quenching. It transforms the entire beta to alpha phase of toothed and irregular boundaries. However, while cooling by slow rate results less irregular grain boundaries. This structure is weaker than produced in the rapid cooling but stronger than equiaxed alpha structure which is producing when annealing at 800^{o}C [32].

CP titanium is used for many structural applications. For example, it is used in military applications (armour, protective linings), in naval applications [1], petrochemical [5] & reaction vessels where formability and corrosion resistance are important. It is also used in structural integrity like landing gear components in Boeings [6] for its high specific strength. As titanium has good mechanical property at elevated temperature, it is used in automotive, nuclear and power generation industries [4], outer cover of turbines, power units for aircraft [6] and hot water heater units [4]. As titanium is also biocompatible, it is used in human bone replacements [7]. It also used in condensers, heat exchangers, evaporators, cryogenic vessels [33, 34] fittings, flanges and valves [2] because of its enhanced thermal conductivity compared to stainless steel [35].

2.2. LASER BEAM WELDING

LBW is used to join metal pieces by the use of a laser. The beam of LBW provides high power density (10^4 MW/m^2), which facilitates for narrow, deep welding, high cooling rate and high welding rates [36]. So the quality of welding is very high. The range of spot size of the laser is in between 0.1 mm to 10 mm. The depth of penetration in a LBW is directly related to the amount of laser power output; however it also depends upon the focus point (defocusing distance). The welding speed is depending on power supply, properties and thickness of the work pieces. As per necessity of application either continuous wave or pulsed laser beam can be used. Pulse laser is used for thin materials such as thin film, while continuous wave laser beam is used for thick materials. Materials like carbon steel, HSLA, stainless steel, aluminium and titanium can be welded by using LBW. However, high-carbon steels produce crack due to high cooling rate in LBW [37].

Figure 2.1 shows a flow sheet of processing steps involved in laser beam welding.

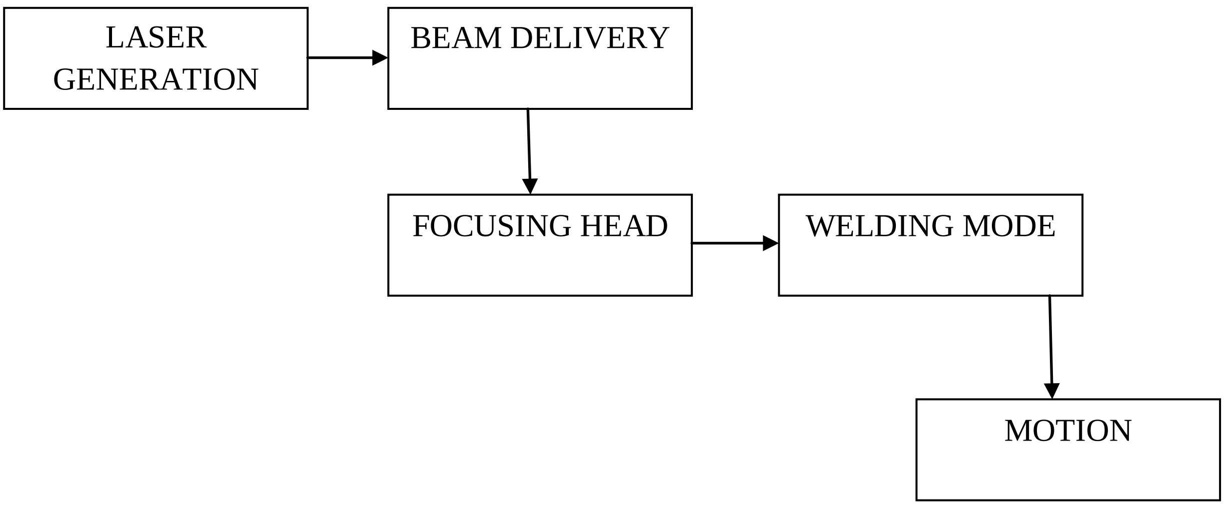

Figure 2.1 Flow sheet of processing steps involved in laser beam welding.

Laser beam is travelling from laser generation chamber to weld surface through the use of beam delivery and focusing head, by different welding mode.

2.2.1 Laser generation

Generation of the laser beam can be done by the use of laser active medium such as gaseous, liquid and solid, which is stimulated by pump energy. The electrons of the atoms get excited after pumping the energy into the medium and jump to a high energy state. However the excited state is not stable and then the excited electron wants to return back to the low energy state by emitting the excess energy gained in the form of photon and known as spontaneous emission. The incoming photon strikes the electron, which is coming from the higher energy state to a low energy state producing a new photon. The photon released during this stimulated emission travels in the direction of the incoming photon with same wavelength and phase. Then the photons are emitting in all directions, but some photons strike the resonator mirrors as a result of reflected back. This laser inversion in the energized state leads to formation of laser generation. To achieve high performance and good quality beam, the shape of the mirrors, size and length of the resonator must be maintained. In a resonator, one mirror is fully reflecting while the other one is partially reflecting for leaking of laser beam as shown in the figure 2.2.

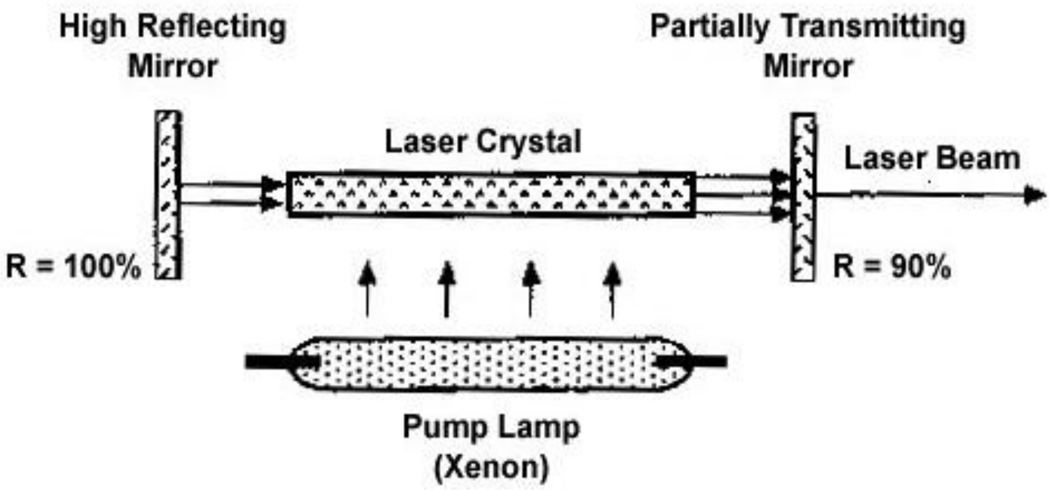

Figure 2.2 the schematic representation of laser generation

2.2.2 Beam delivery

The beam is delivered to the welding area as shown in figure 3.3 with shape and size by using optical fibres, mirrors, telescopes and other optical elements.

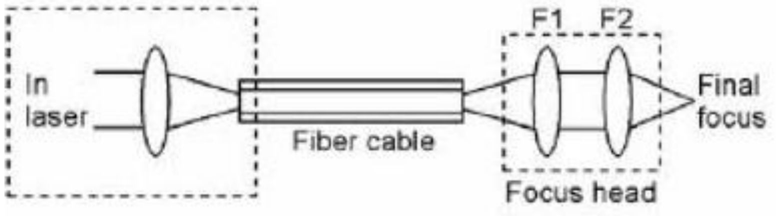

Figure 2.3 shows the laser beam delivery from generation to the work surface

2.2.3 Focusing Head

The laser energy is delivered to the focus head. The focus head as shown in the figure 2.3 consists of lenses of different focal length, which focuses the laser beam on to the work surface. Spot diameter is increasing with increase in focal length of lens [38]. Optics is used to provide a reduced spot diameter for different application in a higher power input laser.

2.2.4 Operation mode

Operation mode in the laser welding depends on three factors:

I) Intensity distribution
II) Energy density
III) Power output

I) Intensity distribution:
Distribution of laser beam intensity across the beam diameter depends on several factors such as the configuration of the resonator, optical fibre, lenses and apertures [39]. There are two types of intensity distribution.

a) Gaussian Mode:
It is an ideal distribution with maximum intensity at the centre of the laser beam and a decrease in intensity with increase in radius across the beam as shown in the fig 2.4 (a).The mode order TEM00 is known as Gaussian mode. This mode is suitable for laser cutting. In this mode, a steady laser beam with concentrated circle of diameter d= 0.18 mm is appearing at the focus point.

b) Donut Mode:

Intensity of the laser at the centre of the beam is zero. However, intensity increases with radius across the beam up to certain point and subsequently decreases to zero as shown in the fig 2.4 (b). The mode order TEM_{01} is known as Donut Mode. In this mode, a steady laser beam of diameter d=0.36 mm with a dark spot at its centre portion is appearing at the focus point.

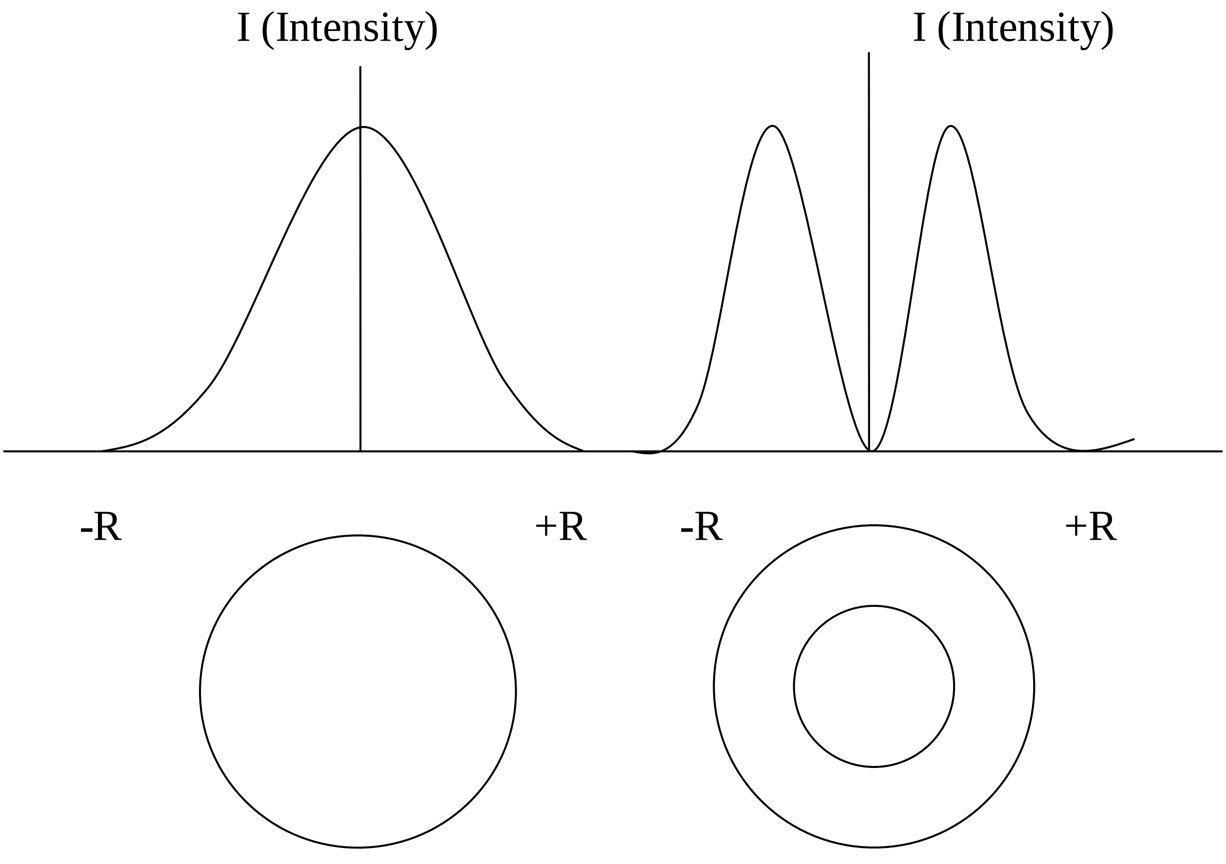

Fig 2.4 (a) Fig 2.4 (b)

Fig 2.4 (a) shows intensity distribution of Gaussian Mode and Fig 2.4 (b) shows intensity distribution of Donut Mode

II) Energy density:

There are generally three types of welding based upon the energy density. a) Conduction, b) penetration, c) keyhole [40]

a) Conduction welding:

This mode of welding is occurring at low energy density, forming a low welding depth on the surface of the specimen as shown in the figure 2.5. In this welding, work piece is welded above the melting temperature without vaporising. It has low coupling efficiency. It has large application in welding of very thin work pieces like foil, wires, thin tubes and enclosure etc [41].

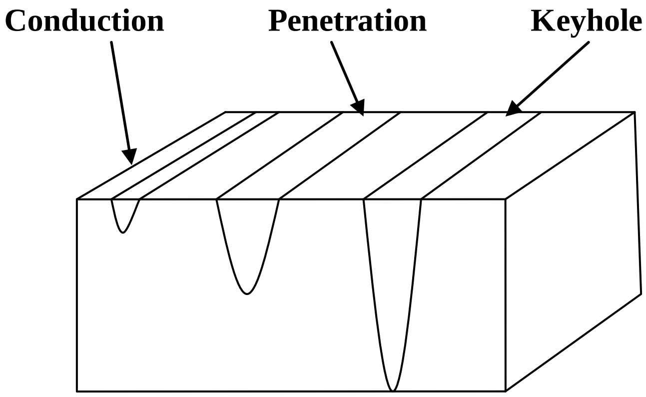

Fig.2.5 shows schematic representation of conduction, penetration and keyhole welding

b) Penetration welding:

This mode of welding is achieving at medium energy density, forming a moderate welding depth as shown in the figure 2.5. In this welding, the work piece is heated above vaporisation temperature. It has high coupling efficiency as compared to conduction welding. It is generally used for welding very thick material and hard material (ceramic) [42].

c) Keyhole welding:

This mode of welding is achieving at high energy density forming a key hole as shown in the figure 2.5. In this welding, the work piece is heated above the evaporation temperature. It has high depth of cutting with very fine cutting precision. It is generally used for cutting thick and hard material.

III) Power output:

There are two types of welding based upon laser power such as a) continuous wave welding b) Pulsed wave welding

a) Continuous wave (CW) welding:

In this welding (Fig.2.6 (a)), steady laser beam power is supplied i.e. reflection of laser beam among the resonator mirrors is generated constantly. Fraction of this radiation exits the resonator steadily through the partially reflected mirror over a period of time. As the resonator is able to supplying continuous laser beam, resulting deeper penetrations in a thicker material. Dissimilar metals can be welded in CW mode.

b) Pulsed welding:

Pulsed welding (Fig.2.6 (b)), the laser is basically switched on and off very quickly. Here the average energy input into the work piece reduces. So Pulsed welding is used for materials, those are highly sensitive to heat. This process takes a millisecond to complete each cycle. Ripple effect of welds can be made by pulsed welding. So it is used for seam welding [43]. Pulsing is often used for piercing and frequencies range from 100 Hz to 10 kHz.

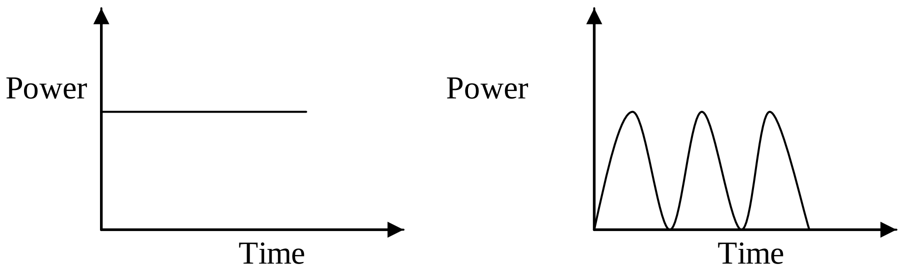

Fig. (a) Fig. (b)

Fig.2.6 Shows power v/s time graph in a laser beam welding

2.2.5 Motion

Laser welding can be prepared with either motion of work piece or motion of laser or combine of both [44].

1. Moving Work piece: the work piece can be moved to form a continuous weld with fixed laser. This can be performed with rollers E.g. CO_2 laser welding

2. Moving Laser: Laser beam delivery in a optical fibre and lens system can be mounted on a robotic systems or industrial unit equipment automation. The laser is moved around the unmovable work piece to be welded. Complex and 3D welds are produced.

3. Both work piece and laser moving: Automatic productions are facilitated by automation unit. It reduces human effort.

2.3 LASER EQUIPMENT

There are two types of lasers (solid and gas) are commonly used [45].

2.3.1 Solid Laser:

In this laser, a solid state laser medium is used. This is generally cylindrical in shape and size of approx. 20mm dia. and 200mm length [38]. Generally Yttrium Aluminium Garnet crystals doped with Neodymium ions is used as laser medium in aNd: YAG laser. Ruby laser and Yt-YAG laser are also solid laser. This laser operates in both pulsed and continuous mode at wavelengths of order of 1 mm, which is smaller than gas lasers. This laser medium is excited by the enclosed flash lamp consists of Kr or Xe. Power output for ruby laser and Nd:YAG laser are 10–20 W and 0.04–6,000 W respectively. Optical fibres are employed to deliver the laser beam to the weld area. This cable is having a central core with cladding region that acts as a mirror. The diameter of the core depends upon the spot size and input laser power. This laser assists further into industrial unit automation equipment and robots due to use of flexible optical fibre. Power input to the laser medium decides the quality of laser beam.

2.3.2 Gas Laser:

Gas lasers use mixtures of gases like N, He and CO_2 as a laser medium for CO_2 laser. It uses low current, high voltage power sources to excite the atoms in the gas mixture. Both continuous and pulsed mode lasers can be operated at wavelength of 10.6 µm. In this laser, optical fibres are not used as it is being destroyed by the absorption of high wavelength, so a mirror and rigid lens delivery system are used. Power outputs (max. 40kW) can be achieved in a gas laser, which is higher than solid laser. Similarly gas lasers like He-Ne laser is used for low power laser beam application and it radiates laser beam in the visible spectrum.

2.4 LASER WELDING PROCESS PARAMETERS

Carefully handling the process parameters provide sound laser welding. The quality of laser welding depends upon various parameters such as laser power, welding speed, spot diameter, power density, pulse width, pulse repetition rate, pulse energy, gas flow rate, defocusing distance beam angle and nozzle design.

Laser power: It is the required power output for welding. It affects the beam quality. Larger power output gives good quality beam.

Welding speed: It is the distance welded in a unit second. It controls the micro hardness, bead width and depth of penetration [46, 47].

Spot diameter: It is the diameter of laser beam which strikes the weld part and it controls the depth of penetration and bead profile.

Power density: It is the power per unit area and it controls the weld penetration [47] and depends on the fibre type, core diameter, focal point, power output and spot diameter.

Pulse width: The pulse width is the duration of the laser pulse. The units are in milli seconds. It controls the heat into the weld.

Pulse repetition rate: It is the number of flash lamp pulses per second. It controls the heat into the weld.

Pulse energy: The pulse energy is the energy contained within a pulse and is a product of peak power and pulse width.

Gas flow rate: It is the amount of gas flow into the weld per unit time. It is affected by temperature and controls the weld quality [48].

Beam angle: It is the angle of laser beam at which weld takes place and it controls the deep penetration [48].

Nozzle design: Conical and ring nozzles are used to increase the coupling between the incident laser beam and the weld surface and prevent the formation of oxides respectively.

2.5 LASER WELDING PRECAUTION

Cover gas: Argon, helium or nitrogen inert gases are used to prevent the oxidation of the weld zone and cool the work piece to minimizing thermal stress. The high energy density of the focused laser beam can be saved.

Material selection: Materials reflectivity should be less as possible. Material like steel should have carbon content under 0.12% otherwise it will produce brittle joint due to high cooling rate of LBW subsequently decreases the mechanical property.

Joint design and fit up: The position of the joint under the laser such that the joint should not miss the focused spot. Close fit up at the joint interfaces is required for sound weld and the gap should be zero. Gap tolerances, which are depending on material thickness, beam diameter, welding speed and beam quality [49].For good quality weld, the gap tolerance should be 0.1mm [50].

2.6 DEFECTS IN LBW:

Pores or voids: It is produced by unstable keyholes, entrapment of gases [51] or vapours, evaporation of metal from the bottom tip of keyhole [52] and turbulent flow of molten metal [53].It is decreasing by increasing cooling rate or increase the speed of welding [54] and by decrease in the laser power [55] by using shielding gas that can be dissolved in the molten metal [56].

Weld cracking: The large solidification shrinkage, high coefficient of thermal expansion and low melting point inter-metallic compounds are the main cause for weld cracking [57]. This can be minimised by taking various parameter suitable to the material properties.

Oxide inclusions: Due to materials strong affinity to oxygen [58]. It can be reduced by using appropriate shielding gas.

Loss of alloying elements: Due to presence of low boiling point and high vapour pressure material in a alloy having high melting point material [59].

Under fill defects: when the laser beam moves forward, the molten metal cannot refill all the depressions at the bottom of the weld. So under fill may form.

2.7 ADVANTAGES

High power density, narrow heat-affected zone (HAZ), small distortion, minor change in microstructure, excellent controllability, flexibility on variety of product geometries and materials, the small space required for the laser beam to access the parts to be welded, possibility to join dissimilar materials, high scanning velocity and high productivity are the advantages. LBW is suitable for precision welding. It can also eliminate secondary processes and increase high productivity with high efficiency [60].

2.8 APPLICATION

Laser welding has wide application on various fields like aerospace industry [61], steel industry [62], electronic industry, plant and apparatus engineering, medical industry [63], automotive industry [64].

2.9 ADVANTAGES OF LASER BEAM WELDING OVER OTHER NORMAL FUSION WELDING

The heat input to the work piece is very low in a laser welding as compared to the normal fusion welding. Both weld bead and heat affected zone are narrower and deeper in a laser welding with respect to the conventional welding due to its high power density [65, 66]. In a welding of sheet, the deformation and distortion produced by TIG welding is more than laser beam welding [67]. In a welding of Ti6Al4V sheets, the top and bottom widths of Fusion Zone in LBW are 1.32 mm and 0.8 mm, while in TIG welding are 4.97 mm and 4.11 mm [67].The highest angular distortion for LBW and TIG are 2.31and 5.51 respectively. The cooling rate is very high in LBW as compared to the normal fusion welding. Fine grains are obtained at the fusion zone due to narrow weld bead results in high cooling rate [68].

2.10 EFFECT OF PROCESS PARAMETER ON LASER WELDING OF DIFFERENT MATERIALS

Laser power:

With increasing laser power, the penetration depth increased but has less effect on both weld profile and heat effected zone (HAZ) width [69] however increasing laser power at slow weld speed leads to increase in all bead parameters such as depth, width[70]. By increasing laser power from 2 to 3 kW in a LBW of 304L austenitic steel, the penetration depth increased from 1.8 mm to 2.7 mm [71]. Similarly in LBW of stainless steel, the penetration depth increases from 0.4 mm to 0.8 mm with increasing power from 580W to 1420W [72]. The heat input increases with increase in laser power, which results coarse grains and more precipitate concentration in fusion zone [73] of AZ31B magnesium alloy material [74]. Increase in peak power leads to increase in penetration depth in a pulsed LBW of Ti6Al4V material [75]. In a LBW of AZ91 and WE43 magnesium alloys, the penetration depth is increasing with increase in laser power [76, 77]. High beam power leads to deep and wide beads on laser welded magnesium alloy but reduces both ripples and crowning [78]. In a LBW of austenitic stainless steel, i) the mechanical property such as tensile strength increases with increase in laser power up-to some extent after that it starts decreasing [79] due to formation of wider HAZ at higher power [80] however, the impact strength increases with increasing laser power [79] and when laser power decreases at high welding speed the tensile strength decreases due the lack of full joining [79]. With increasing laser power at slow welding speed results in formation of residual stresses at the weld pool and leads to decrease in tensile strength [81].

Welding speed:

The fusion zone size increases with decreasing in welding speed as a result of decrease in aspect ratio resulting unacceptable profile [71]. In a laser welding of stainless steel sheet, when the welding speed increases the bead parameters such as depth of penetration, bead width and area of penetration decreases however, depth of penetration and area of penetration are increasing with welding speed due to less plasma blocking at higher range of welding speed [72]. When welding speed increases results heat input decreases leads to finer grains are achieved in the fusion zone of AZ31B magnesium alloy material along with moderate concentration of precipitates [82]. The weld width decreases with increasing welding speed at a constant beam diameter for laser welded S355 low carbon steel [81]. Amount of porosity formation is decreased with the decrease in welding speed due to full penetration for a LBW of V-4Cr-4Ti[12]. In a LBW of austenitic stainless steel, the impact strength decreases with the increasing welding speed as weld reduces the toughness and make more brittle by the formation of smaller weld pool size and of the higher cooling rate [79].in a laser welding of Ti6Al4V alloy, the micro hardness in the fusion zone increases with the welding speed [83] and heat input decreases with increase in welding speed leads to high cooling rate obtaining increase in micro hardness [84, 85].

Effect of defocusing distance:

The penetration depth is decreased with increasing or decreasing defocusing distance due to decrease in laser density in a laser beam of laser welded 304L austenitic steel. The optimum value of defocusing distance to obtain an acceptable weld profile for 3mm and 5mm thickness is -0.2mm and -0.4mm respectively [71]. In a CO2 LBW of AZ91 and WE43 Mg alloys, an acceptable weld could be acquired for a position of focus on or 1 mm below the surface of the work piece [77, 86, 87]. In a LBW of magnesium alloy at 2.5 kW CO2 laser, when the focus point is on the surface of work piece, the most excellent welds are obtained for thin plates (<3mm). Whereas for thick plates (5 to 8 mm), focal position is adjusted 2 mm below the surface of work piece for excellent weld [88, 89]. LBW of austenitic stainless steel with either a focused or defocused laser beam in a slow welding speed has no significant effect on the tensile strength [79].

Laser beam diameter:

In a laser welding of AISI stainless steel the width of bead increases and the penetration depth of weld decreases with the diameter of beam [90]. The width of weld bead increases and the depth of weld decreases with the beam diameter due to interaction with metal increases and reduction of power density respectively [91]. All welds achieved with a beam diameter of 0.78 mm are significantly wider than the corresponding welds achieved with a beam diameter of 0.38 mm, for the same travel speed for laser welded S355 low carbon steel [81]. It was shown that just maintaining a constant power density does not guarantee the same depth of penetration, whilst beam diameter is varied. In such a case much greater depth of penetration was achieved with bigger beam diameters [92].

Effect of type of shielding gas:

In the laser welding of austenitic steel, plasma effect was reduced more by the higher ionisation potential of helium instead of Argon (lower ionisation) and then the weld profile is improved [71]. In a Nd:YAG laser welding of V-4Cr-4Ti,pure argon are used to improve the quality of the welding atmosphere by minimizing oxygen and nitrogen intake.

Beam angle:

In a laser welding of stainless steel sheet, by increasing beam angle from 82 to 98 degree anticlockwise both bead width and area of penetration decreases and the depth of penetration increases [72].

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Chapter 3

EXPERIMENTAL PROCEDURE

3. EXPERIMENTAL PROCEDURE:

3.1 Material and Sample Preparation:

Commercially pure titanium (cp-ti) sheets of 1 mm thick were obtained from the market.The chemical composition of cp-ti is shown on the table 3.1. The size of cp-ti sheets obtained was approx. 250mm × 200mm. For laser welding eighteen numbers of specimens of size 50mm × 50mmwere prepared. Before laser welding, all the specimens were mechanically brushed and cleaned to take out the contamination of the surface to produce defect-free joint. The specimens were cleaned properly with isopropyl alcohol then immersed with 5% NaOH at room temperature for 5minute followed by washing with running water. Subsequently specimens were dried and immersed with 5% turco acid(40%HNO3+4%HF+56% DM water) for 5minute followed by washing with running water and dried. The specimens were then welded by using a CO_2CW laser welding (ML 2000) at ARCI, Hyderabad, India. The laser welding was carried out at different process parameters, shown in table 3.2.Nine different conditions, shown in table 3.3, were designed by varying the process parameters for their effect on laser welding of cp-ti.

Table 3.1 Chemical composition (in wt.%) of cp-titanium used in the present study.

Fe	C	N	H	O	Ti
0.034	0.004	0.004	0.0004	0.134	Balance

Table 3.2 Weld parameters used in the present study.

Welding Parameters	Value
Power in kW	2 & 2.5
Welding speed in m/min	4, 5, 6, 7 & 8
Beam diameter	Gaussian Mode (beam focus diameter 0.18 mm) Donut Mode (beam focus diameter 0.36 mm)
Wave length in µm	10.6
Focal position	At the surface
Gas flow rate in m^2/min	35
Beam angle in degree	90
Focal length in mm	300

Table 3.3Different processing conditions of laser welding investigated in the present study.

Process Conditions	Power in kW	Welding speed in m/min	Beam diameter at focus in mm
1	2.0	5	0.18
2	2.0	6	0.18
3	2.0	7	0.18
4	2.5	6	0.18
5	2.5	7	0.18
6	2.5	8	0.18
7	2.5	4	0.36
8	2.5	5	0.36
9	2.5	6	0.36

Characterization Techniques:

3.2 Dye Penetration (DP) Test:

DP test was carried out at the top surface of welding to find out the soundness of the welding. Initially, a pre-cleaner was used to remove oil, grease and other organic contamination from the surface of the material under test. Then a penetrant ORION 115P was applied and kept it for 20 minutes. Subsequently the surface was cleaned with a penetrant remover ORION 115PR and a developer ORION 115D was applied to find out the defects present in the welding. No welding defect was detected at the end of testing.

3.3 Electron Probe Micro Analysis:

EPMA was carried out in a JEOL SEM. This was performed in the weld-pool region to find out any impurities like C, O, N etc. picked-up during the process of welding. Figure 3.1 shows the EPMA maps of C, N, O, Fe and Ti weld-pool region. An insignificant pick-up of impurities during the process of welding can be seen from the figure 3.1.

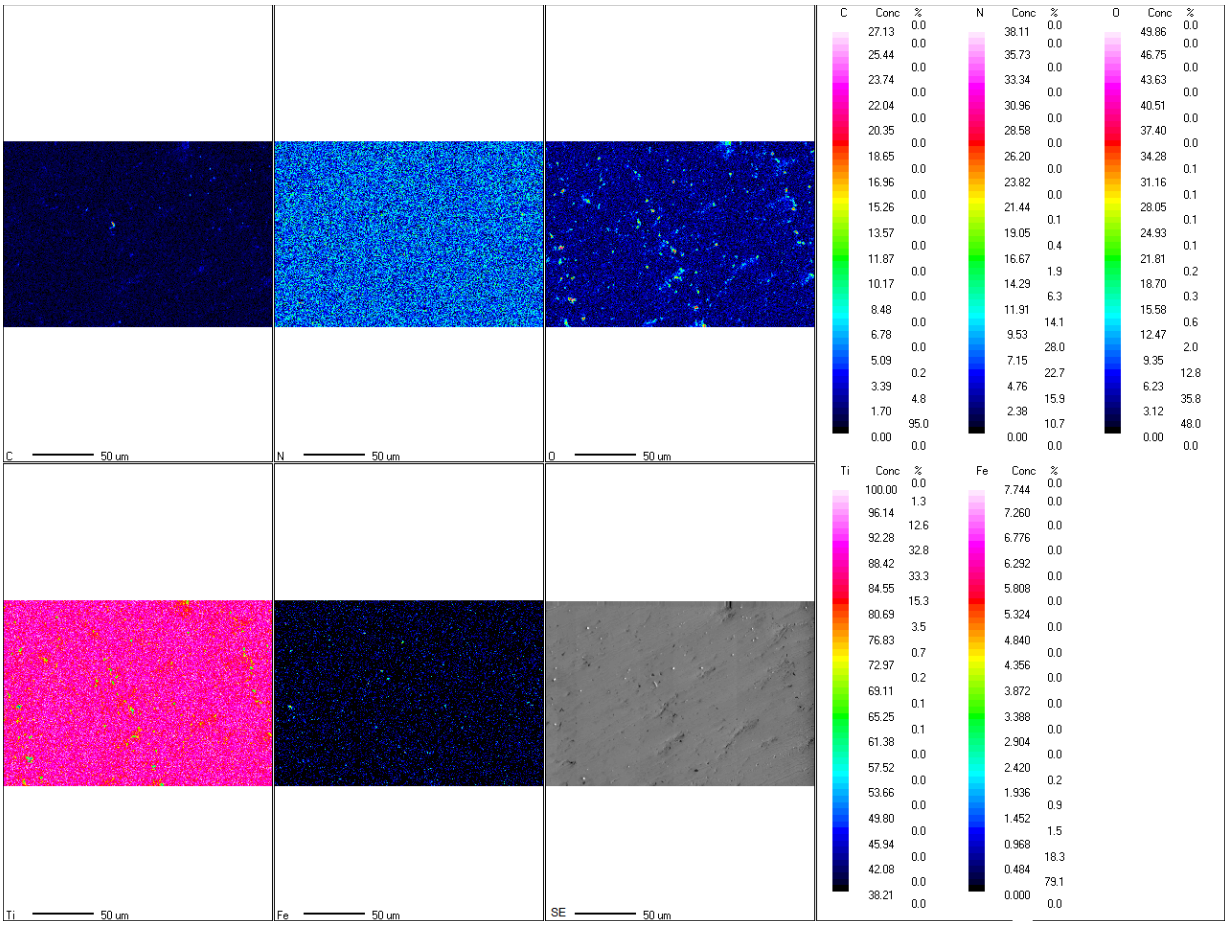

Figure 3.1 EPMA maps of different elements in weld pool of the laser welded cp-titanium.

3.3 Optical Microscopy:

The welded samples were metallographically polished for micro-structural and mechanical properties characterization. The samples were etched with a solution of 100 ml water, 2 ml HF and 5 ml HNO_3(Krolls reagent). The microstructure was analysed by SEIWA, Japan making light optical microscope.

Mechanical property:

3.4 Vickers Hardness:

Vickers hardness was performed in a LECO Micro-hardness tester LM 248AT using 100gf load and a dwell time of 10 sec. The hardness was measure across the welding i.e. from one end to the other end. Five indentations were made in each region of welding and the average hardness value is reported.

3.5 Tensile Test:

Tensile test was carried out in an INSTRON-5967 universal testing machine. A schematic of the tensile specimen with dimensions marked is shown in the figure 3.2.

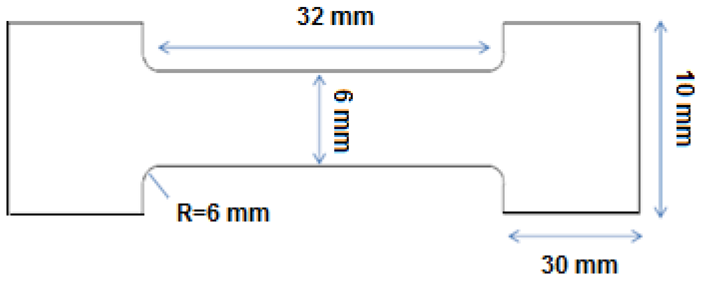

Figure 3.2A schematic of tensile test specimen used in the study.

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Chapter 4

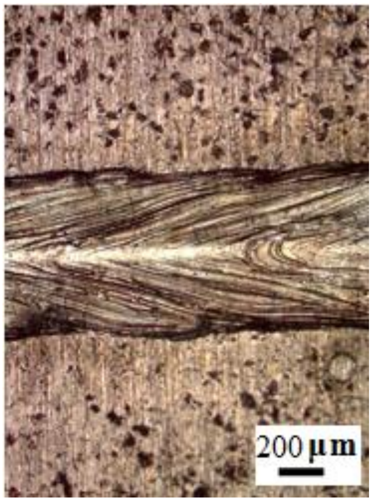
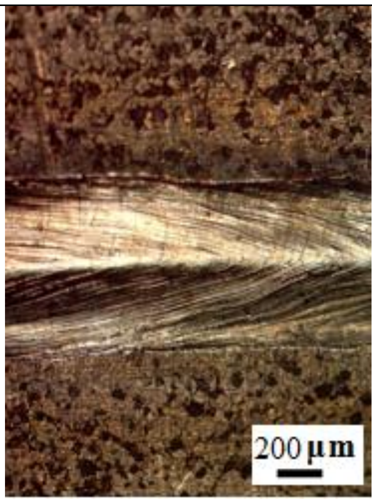
RESULTS

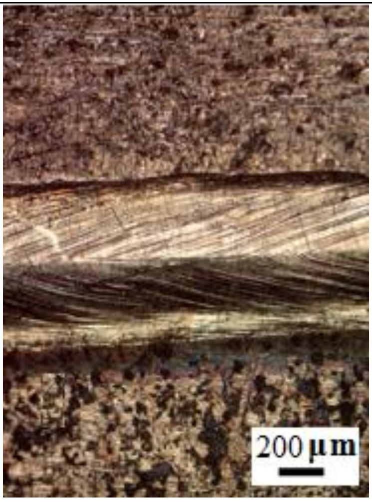
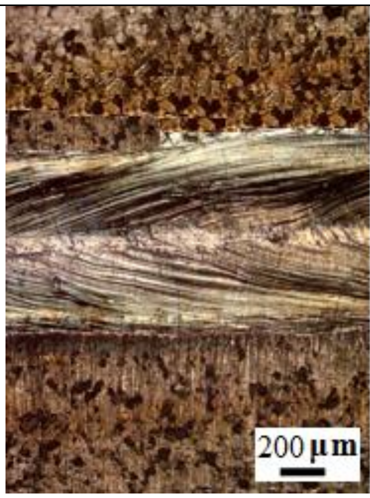
AND

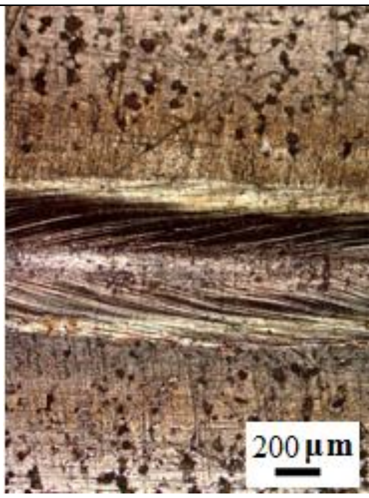
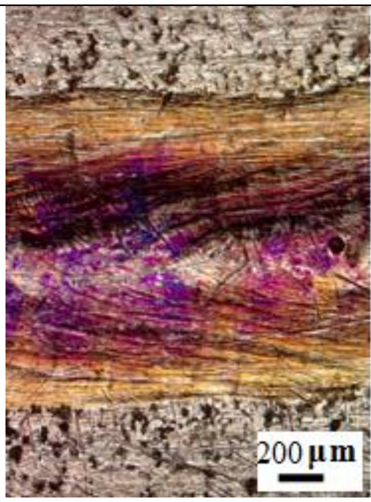
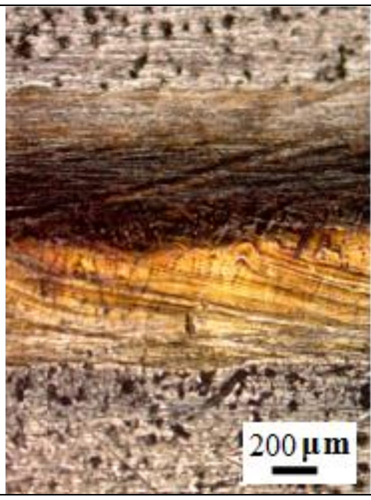
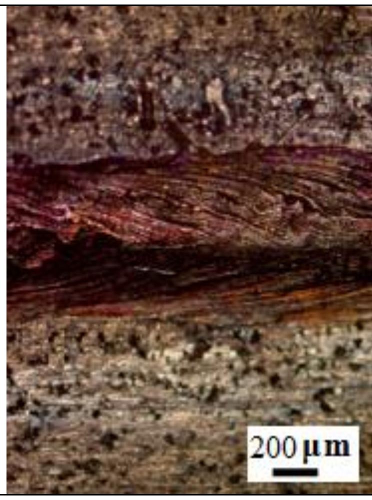
DISCUSSION

4. RESULTS AND DISCUSSION:

Figure 4.1 shows the macrostructure of laser welded cp-ti samples at different processing conditions. The figure clearly shows a decrease in width of weld in the bottom surface of the samples compared to the top surface. It also shows a decrease in width with increase in weld speed and an increase in width with increase in weld power. The Donut mode welding show a larger weld size compared to Gaussian mode of welding.

Processing Conditions	Top	Bottom
1		
2		

3		
4		
5		

6		
7		
8		

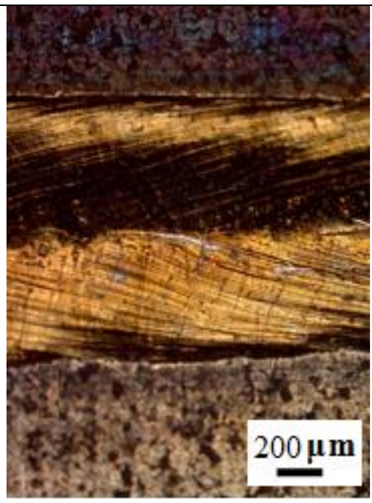
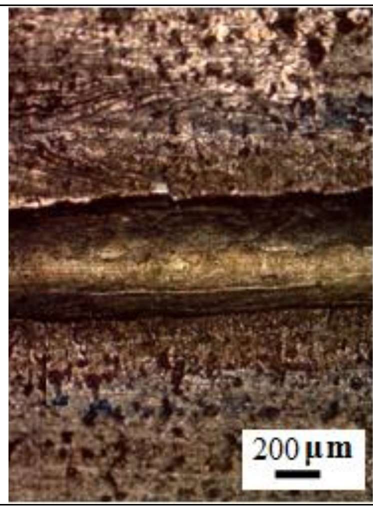
9		

Figure 4.1 Top and bottom weld microstructures of laser welded cp-ti at different processing conditions.

The weld size at the top surface for nine different processing conditions were 910µm, 781µm, 725µm, 851µm, 753µm, 718µm, 1377µm, 1301µm and 1211µm, whereas the size at the bottom surface were 758µm, 654µm, 618µm, 841µm, 641µm, 612µm, 935µm, 757µm and 500µm. From the above data it resulted, the weld size of top bead decreases by increasing the welding speed. In the same way, the weld size of bottom bead is also decreasing with welding speed

It is expected that with increase in laser power, a wider weld pool is observed due to high heat input. A higher welding speed results a lower time of interaction with the material which decreases the weld pool size. Similarly, beam diameter (0.18 mm in case of Gaussian mode and 0.36 mm in case of Donut mode) can clearly explain its effect on the weld pool size. Higher the beam diameter, wider the weld pool is expected.

Figure 4.2 and 4.3 shows the optical microstructures of base metal and weld region (weld-interface & weld-pool) respectively. The base metal had a nearly equiaxed grain structure with an average grain size of 60µm see figure 4.2. The following observations can be made from Figure 4.3:

- The grain size (of both weld-interface and weld-pool region) increases with increase in welding speed.
- The grain size (of both weld-interface and weld-pool region) increases with increase in power input.

- A sharp interface was observed in donut mode compared to Gaussian mode of laser welding. Visible elongated grains were observed in the weld interface of Gaussian mode laser welding.

In contrary to a decrease in weld pool size, an increase in grain size with increase in welding speed size was observed. This may be accounted because of larger growth rate at higher welding speed. A thorough mathematical modelling is required to explain the result more clearly. However, in the limited time frame it was not possible to study the modelling aspect of the present investigation.

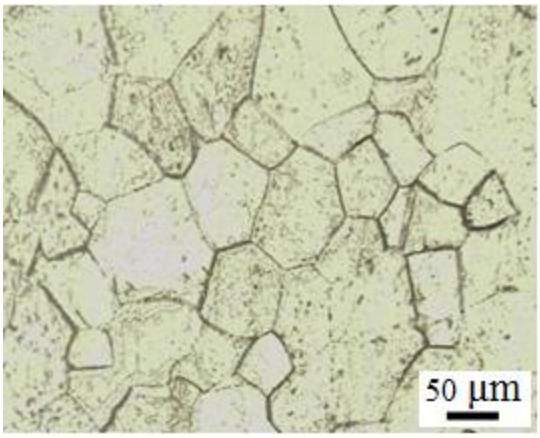
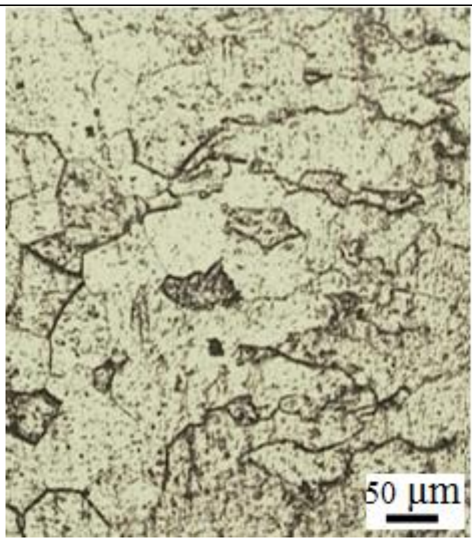
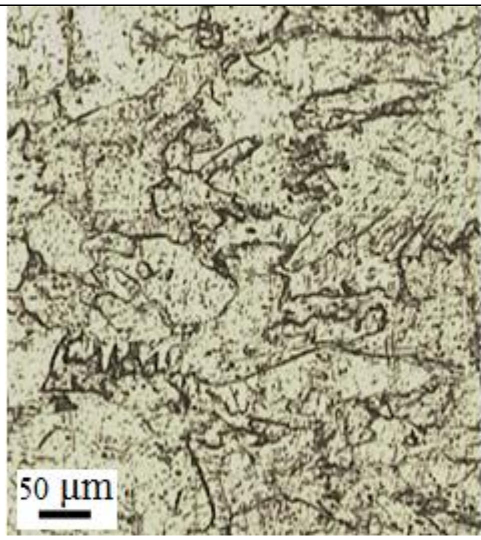
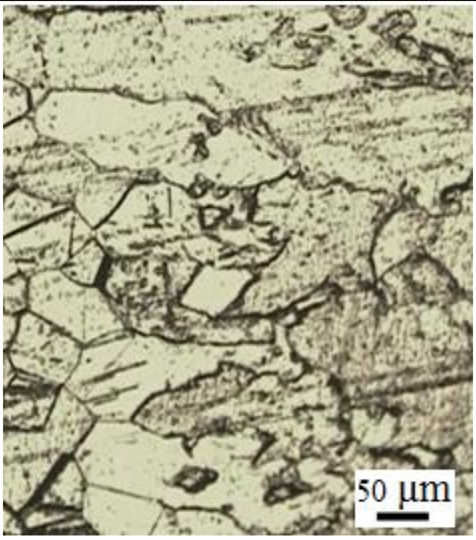
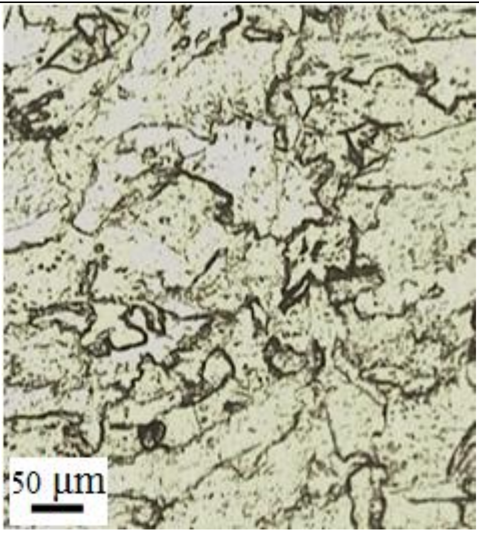
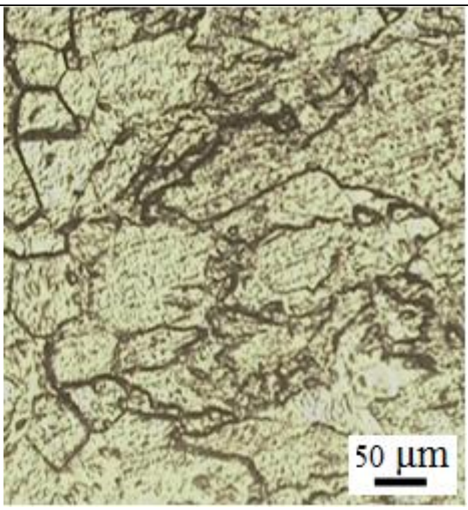
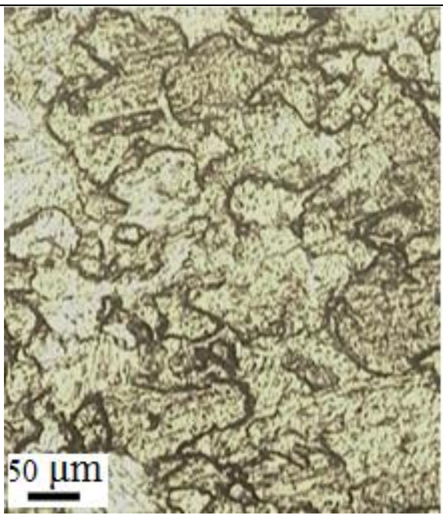
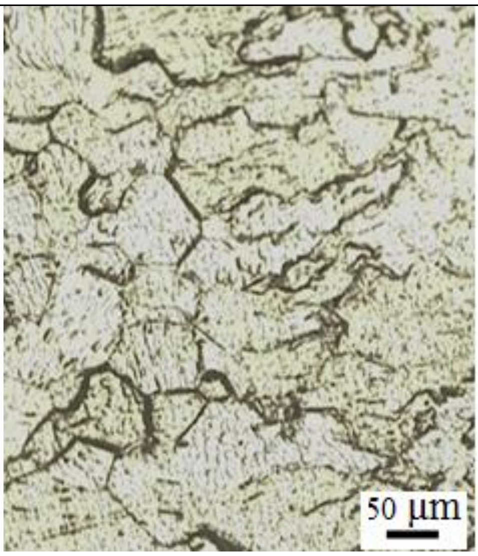
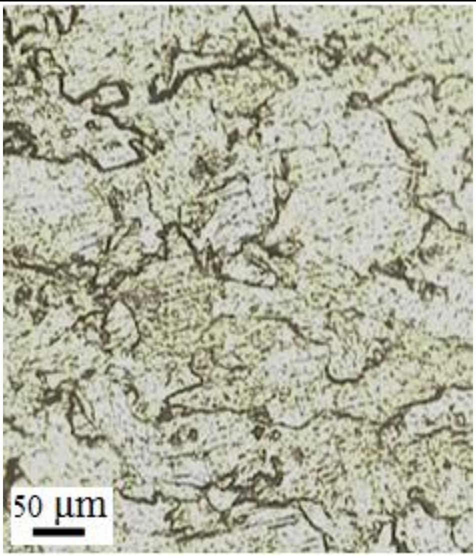
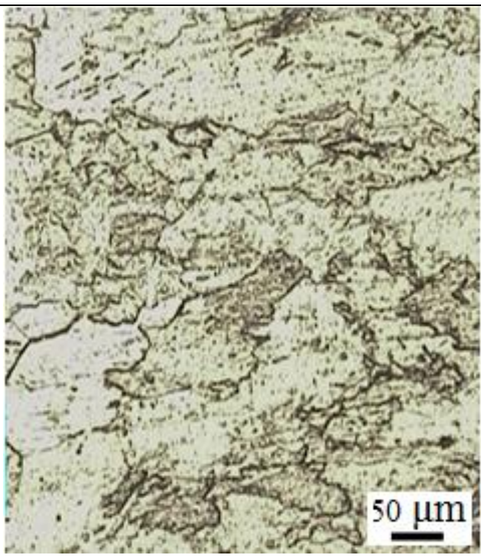
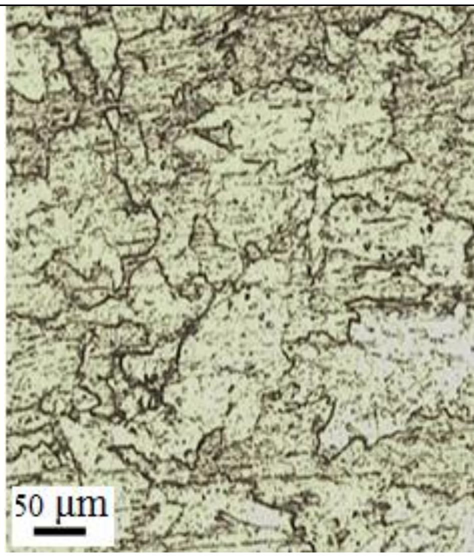
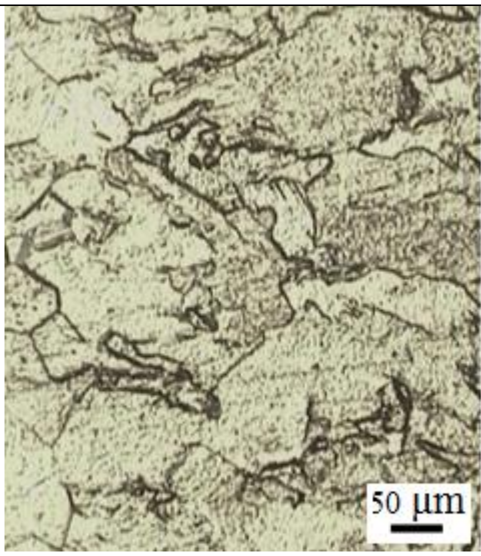
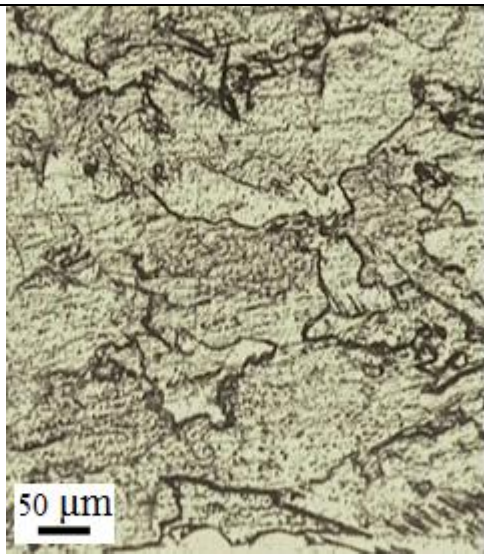
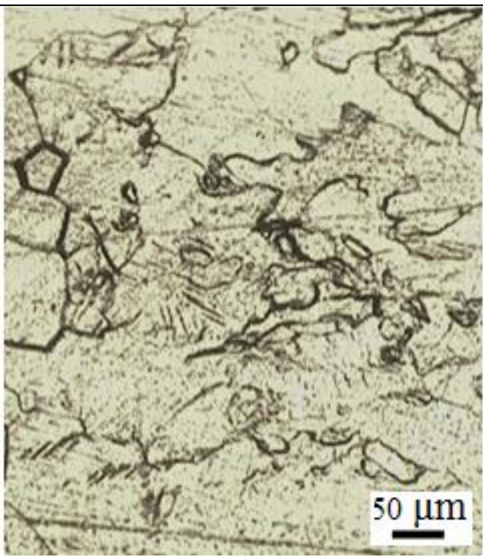
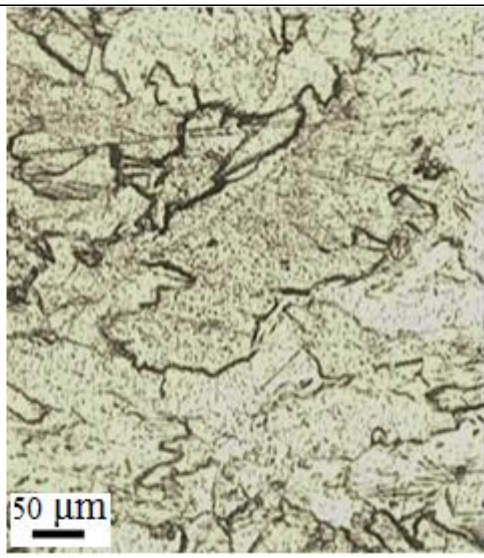


Figure 4.2Optical microstructure of base-metal i.e. as-received cp-ti sheet.

Operational condition	Weld Interface	Weld Pool
1		

2		
3		
4		

5		
6		
7		

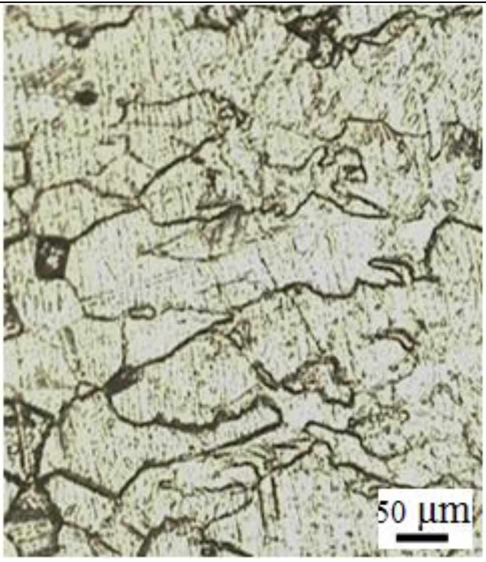
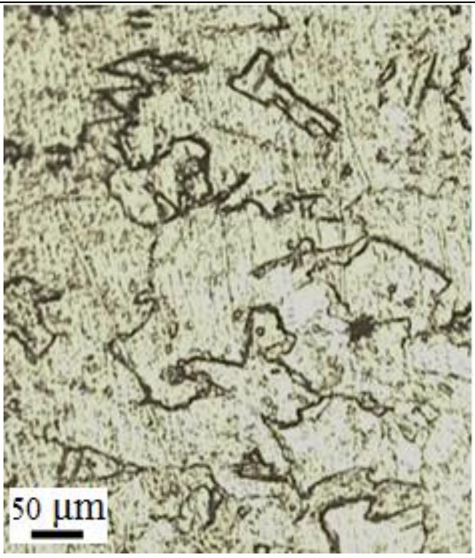
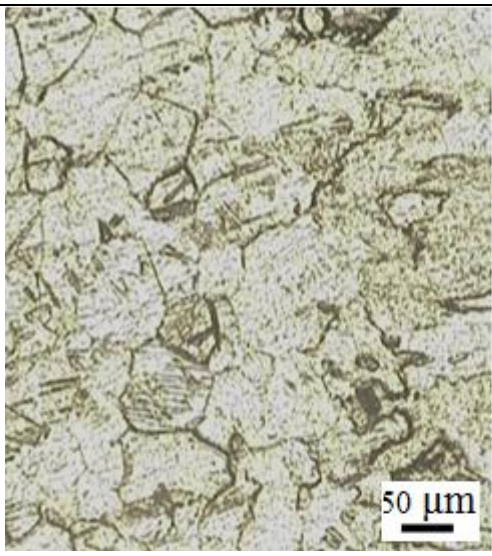
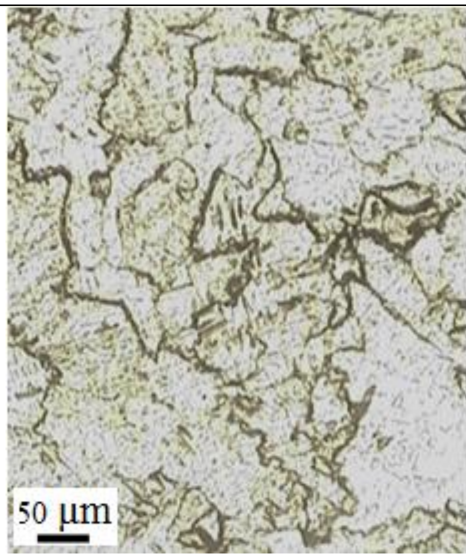
8		
9		

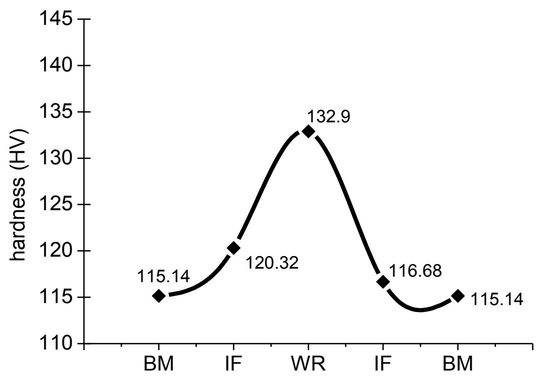
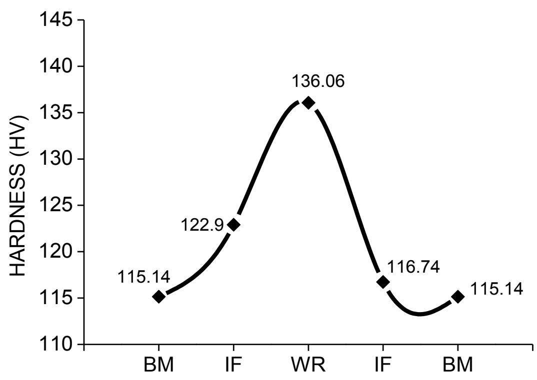
Figure 4.3 Microstructures of weld-interface and weld-pool of laser welded cp-ti at different processing conditions.

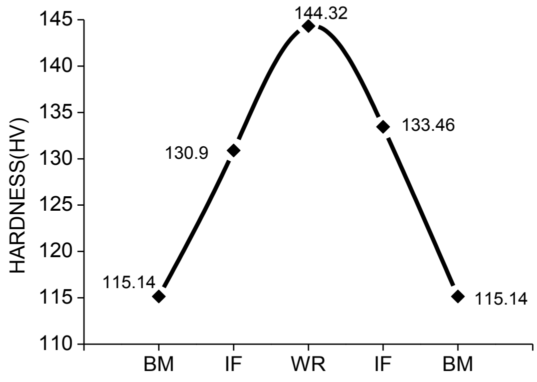
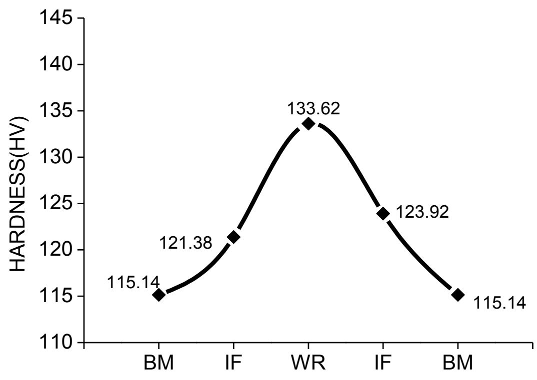
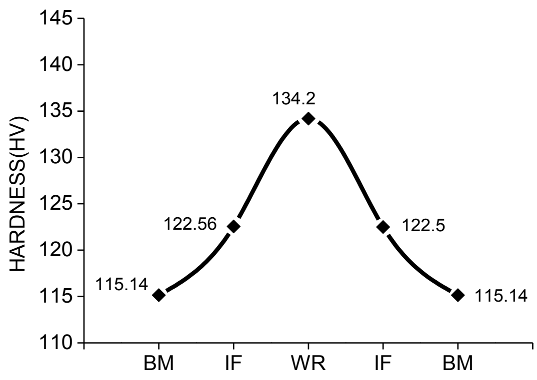
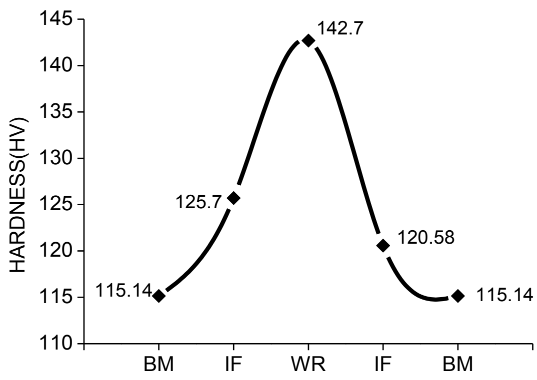
Figure 4.4 shows the Vickers hardness across the welding cp-ti sheet. The hardness values of base-metal (BM), weld-interface (IF) and weld-pool region (WR) were estimated and average values are reported in the figure. The following observations can be made from the figure:

- A higher value of Vickers hardness was observed in IF and WR compared to BM. The value is highest in WR.

- The hardness value increases with increase in welding speed and it decreases with increase in laser power.
- The Vickers hardness is more in the Donut Mode with respect to the Gaussian Mode.

The trend in hardness variation cannot be explained only form the results of grain size developments in laser welding. However, the effect of fluid flow in the weld pools i.e. the flow velocity, interaction time (time of welding), density of fluid etc. It is expected that a higher welding speed result more stress in the material which may have the reason of increase in hardness with increase in welding speed. It may also be noted that the increasing trend was insignificant – only an increase of maximum 11 HV was observe.

Process Conditions	Vickers Hardness
1	
2	

3	HARDNESS(HV) 145 140 135 130 125 120 115 110 144.32 130.9 133.46 115.14 115.14 BM IF WR IF BM
4	HARDNESS(HV) 145 140 135 130 125 120 115 110 133.62 121.38 123.92 115.14 115.14 BM IF WR IF BM
5	HARDNESS(HV) 145 140 135 130 125 120 115 110 134.2 122.56 122.5 115.14 115.14 BM IF WR IF BM
6	HARDNESS(HV) 145 140 135 130 125 120 115 110 142.7 125.7 120.58 115.14 115.14 BM IF WR IF BM

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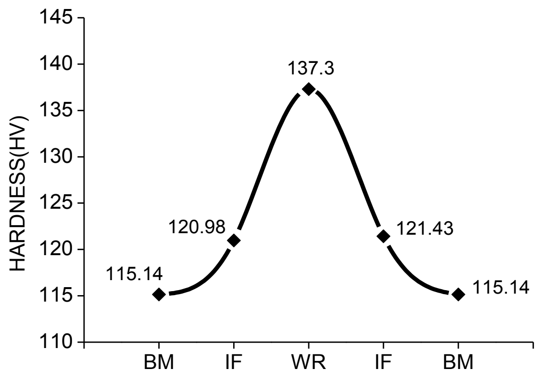
<tr><td>7</td><td>
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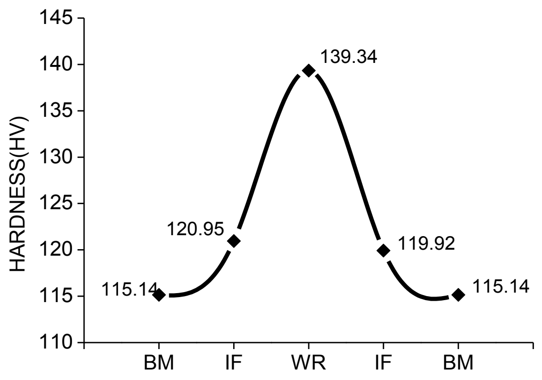
<tr><td>8</td><td>
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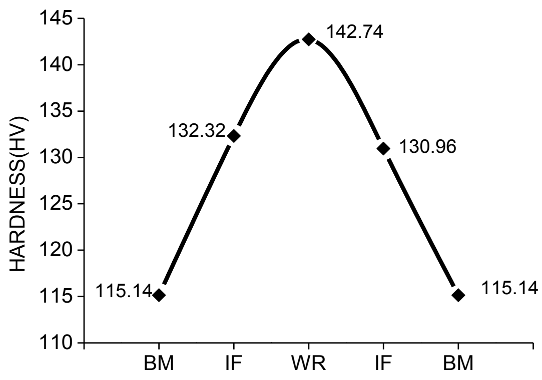
<tr><td>9</td><td>
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Figure 4.4Vickers hardness profiles of laser welded cp-ti samples at different processing conditions.

Figure 4.5 shows the stress-strain diagram of cp-ti samples at different processing conditions of laser welding. The figure clearly shows approximately equivalent mechanical properties (except percentage elongation) of base metal and different laser welded samples. This shows that the laser welding carried out in the present study is a perfect welding. Among the different processing conditions, samples welded under 6 & 7 conditions showed most equal mechanical properties with the base metal.

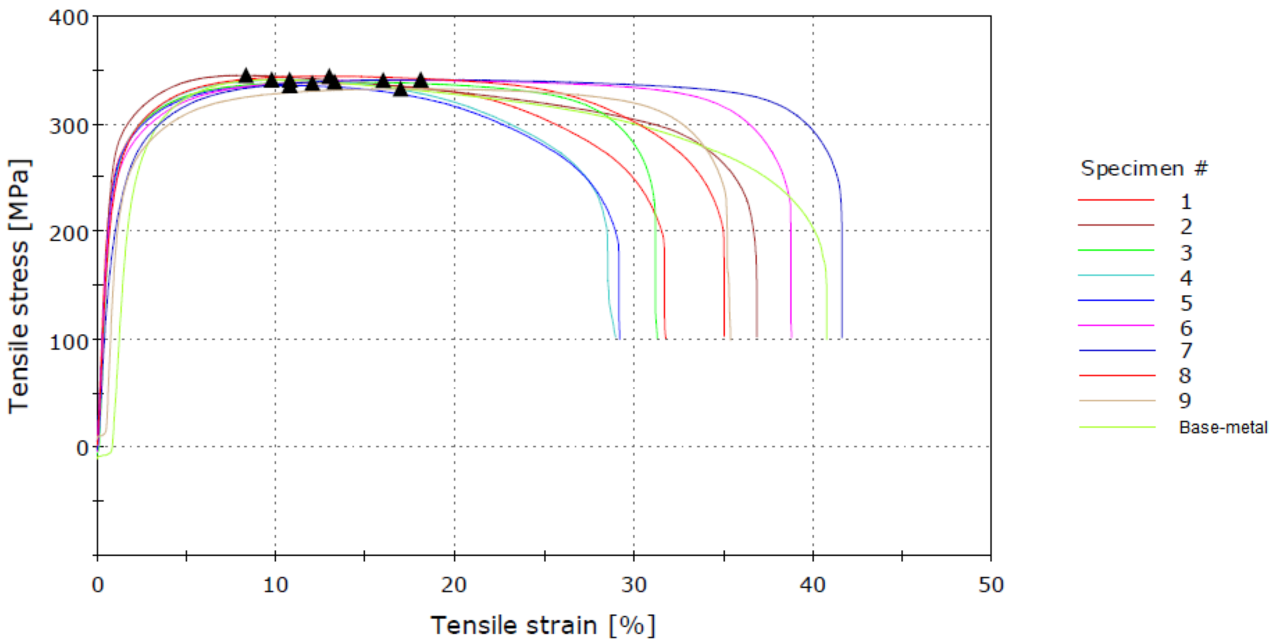

Figure 4.5 Stress-strain plot of laser welded cp-ti samples at different processing conditions.

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Chapter 5

SUMMARY

SUMMARY:

The CO_2 continuous wave laser welding has been employed for the welding of cp-ti sheets of 1mm thickness. The effect of process parameters like welding power, welding speed and welding mode on laser welded cp-titanium is investigated.

It shows that the size of weld region may control by varying the laser power, welding speed and beam diameter. The width of weld in the bottom surface of the samples decreases compared to the top surface. It also shows a decrease in width with increase in weld speed and an increase in width with increase in weld power. The Donut mode welding show a larger weld size compared to Gaussian mode of welding.

The grain size of both weld-interface and weld-pool region increases with both welding speed and power input. A sharp interface was observed in donut mode compared to Gaussian mode of laser welding. Visible elongated grains were observed in the weld interface of Gaussian mode laser welding.

The Vickers micro-hardness values of weld pool region across the weld are higher than both the weld interface and base material. The hardness value increases with increase in welding speed and decreases with increase in laser power. The Vickers hardness value is more at the donut mode compared to Gaussian mode. In the tensile test, all specimens fail in the base metal region signifying that defect free joints are obtained. We observe that the tensile strength, 0.2% yield strength and elastic modulus of all the operation conditions are equivalent. It is observed that process condition 6 is best among all.

FUTURE SCOPE:

The effect of process parameters on laser welding of cp-ti sheets of thickness 1mm has extensively been investigated in the present study. In real applications of cp-titanium, a larger thickness is used and the present investigation may provide an insight for the laser welding of thicker cp-titanium sheets. Hence, the authors suggest a study of process parameters on the laser welding of thicker cp-titanium sheets is essential. Also laser welding of dissimilar materials is a recent (relatively) approach in the field of welding research. This should be exploited. Explanation of results obtained in the present study is one limitation of the present study. The results should be validated through proper mathematical modelling.

Chapter 7

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REFERENCES

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